SUSY searches at ATLAS

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First ATLAS searches for signals of Supersymmetry in proton-proton collisions at the LHC are presented. These searches are performed in various channels containing different lepton and jet multiplicities in the final states; the full data sample recorded in the 2010 LHC run, corresponding to an integrated luminosity of 35 pb^{-1}, has been analysed. The limits on squarks and gluinos are the most stringent to date.

1 Introduction

Supersymmetry (SUSY) is one of the most favoured candidates for new physics, predicting a new symmetry between fermions and bosons and therefore a large number of new particles [1]. There are various reasons why these new SUSY particles are expected to be not too heavy, but accessible with TeV scale energies. SUSY would reduce the so-called *fine-tuning problem* of the Standard Model (SM) and it indicates that the three forces of the Standard Model are unified at very high energies. On the other hand SUSY particles have not been discovered so far and thus need to be heavier than their SM counterparts. In addition a new multiplicative quantum number called R-parity is introduced to forbid strong lepton and baryon number violating terms in the SUSY Lagrangian leading to too rapid proton decay. If the R-parity quantum number is conserved and SUSY particles are heavier than their SM partners, then SUSY predicts a large amount of Dark Matter in the universe. These reasons make the search for SUSY particles a major and important part of the LHC physics program. New SUSY particles could be discovered or if nothing is found at the LHC the SUSY solution to the SM shortcomings will become very unlikely.

At the LHC new SUSY particles are produced in pairs (if R-parity is conserved) and each decays usually via several intermediate steps (cascade decay) to the lightest SUSY particle (LSP). The LSP is only weakly interacting due to cosmological arguments and leads to the most characteristic feature of these SUSY events, which is missing transverse momentum. Since the SUSY breaking mechanism is unknown the mass pattern of the SUSY particles cannot be predicted. The search strategy needs therefore to be quite generic or SUSY model parameter independent. A generic search strategy for R-parity conserving SUSY signatures would include the selection of events with large missing transverse energy and reconstructed particles with large transverse momentum. At the LHC these objects are predominantly jets since the coupling strength of the strong force would cause an abundance of squarks and gluinos if these particles are not too heavy. Squarks or gluinos will cascade decay to jets, several leptons or photons depending on the SUSY parameters and missing transverse momentum caused by the LSPs. The searches for SUSY signatures with R-parity conservation are performed by searching for more events than expected in a number of different channels. These channels explore a large variety of possible
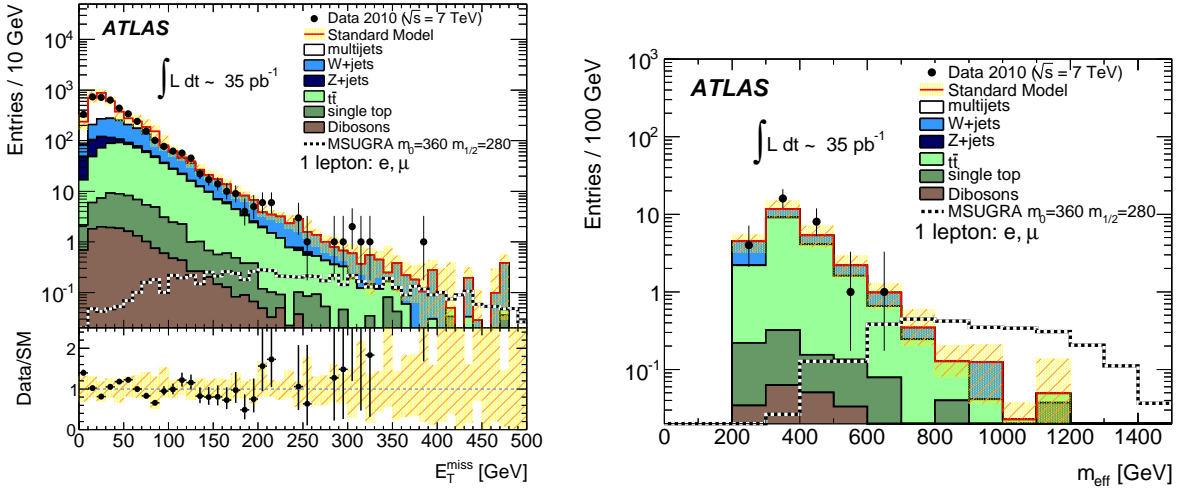
Figure 1: E_T^{miss} distribution after lepton and jet selection (left figure). Effective mass distribution after final selection criteria except for the cut on the effective mass itself (right figure). The plots are made for the electron and muon channel combined. Yellow bands indicate the uncertainty on the Monte Carlo prediction from finite Monte Carlo statistics and from the jet energy scale uncertainty.

signals, e.g. ATLAS studies various different jet (2,3,4) and lepton (0,1,2,3) multiplicities. The main challenge in these searches (and most of the work) is to reliably control the Standard Model background expectations. In the following we assume mostly the 5-parameter mSUGRA as a "general" model for R-parity conserving SUSY. Model-independent limits on an *effective* cross section for new processes in the signal region, including the effects of experimental acceptance and efficiency have also been derived. They can be used to exclude any model of new physics leading to a larger *effective* cross section.

All data presented in this summary are taken in the year 2010 at the ATLAS experiment [2] in LHC proton-proton collisions at 7 TeV centre-of-mass energy, using a data-set corresponding to an integrated luminosity of about 35pb^{-1}.

2   Searches with Jets, a Lepton and Missing Transverse Momentum (1 lepton channel)

The search in a channel with jets, exactly one muon or electron and significant missing transverse momentum E_T^{miss} constitutes the first ATLAS SUSY result [3]. This channel could be studied first due to the large reduction of the potentially dangerous QCD multijet background. Requiring one muon or electron reduces this background by several orders of magnitude. The left plot of Figure 1 shows the missing transverse momentum distributions after requiring three jets and one muon or electron. The data is compared to the prediction from Monte Carlo. Only the QCD prediction from PYTHIA was scaled with a k-factor depending on the muon or electron selection. The figure shows that at high E_T^{miss} the main background comes from W+jets events and events from top pair production. The data is in agreement with the expectations. The signal region is defined by cuts on $E_T^{miss} > 125$ GeV, $E_T^{miss} > 0.25 m_{eff}$ and $m_{eff} > 500$ GeV. The effective mass m_{eff} is the sum of the p_T of the leading three jets, the p_T of the lepton and E_T^{miss}. The cut on E_T^{miss} thus scales with the total transverse momentum in the event. The smallest of the azimuthal separations between the jets and missing transverse energy vectors $\Delta\phi(\text{jet}, \vec{P}_T^{miss})_{min}$ was required to be > 0.2 in order to remove QCD events caused by mismeasurements or heavy flavour decays. Finally, the transverse mass M_T, calculated with the lepton and the missing transverse momentum 2-vector $\vec{P}_T^{miss}$, is required to be > 100 GeV in order to reduce the
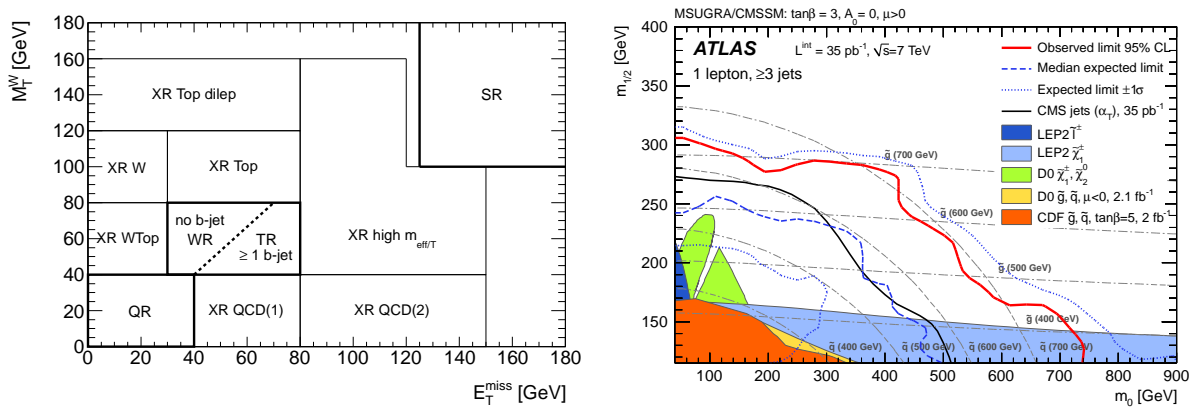
Figure 2: The left figure shows the position of the signal region (SR) and the main control regions (CR) in the (E_T^{miss}, M_T) plane. The top enriched control region (TR) and the W+jets enriched control region (WR) are separated by the existence of a b-tagged jet candidate among the three leading jets. The XR regions correspond to extra validation regions. The right plot shows the observed and expected 95% CL exclusion limits, as well as the $\pm 1\sigma$ variation on the expected limit, in the combined electron and muon channels. Also shown are the published limits from CMS, CDF, D0, and the results from the LEP experiments.

background from W bosons.

In order to determine the background predictions for the signal region, ATLAS has defined several control selections. The W and top control regions e.g. are defined by keeping the jet and lepton selection criteria as for the signal region, but requiring $30 < E_T^{miss} < 80$ GeV and $40 < M_T < 80$ GeV to enhance events with W bosons. In order to determine the amount of W+jets and top pair events separately a b-tagged jet is required for the top control region, and a b-veto is done for the W control region. The positions of the signal region (SR) and the main control regions (CR) in the (E_T^{miss}, M_T) plane are shown in Figure 2. The transfer of the top and W normalisation factors measured in the control region to the signal region is done by Monte Carlo and the uncertainty is carefully studied, including a validation in additional regions (see also Figure 2).

In the electron selection 1.81 ± 0.75 events are expected and one event is found in the data. For the muon selection 2.25 ± 0.94 events are expected and again only one event is found in the data. The small deficit results in an observed limit which is better than the expected limit. The limits are then derived from the profile likelihood ratio. A model independent 95% CL upper limit on the effective cross section for new processes in the signal region, including the effects of experimental acceptance and efficiency, of 0.065 pb for the electron channel and 0.073 pb for the muon channel is derived. Limits are also set on the parameters of the minimal supergravity framework, extending the limits set by the Tevatron experiment by far. The observed and expected upper limits are shown in Figure 2. For $A_0 = 0$ GeV, $\tan\beta = 3$, $\mu > 0$ and for equal squark and gluino masses, gluino masses below 700 GeV are excluded at 95% confidence level.

3   Searches with Jets and Missing Transverse Momentum (0 lepton channel)

The second analysis released by ATLAS only a few weeks later was the search in channels with jets and missing transverse momentum [4].

In order to achieve a maximal reach over the $(m_{\tilde{g}}, m_{\tilde{q}})$-plane, several signal regions are defined. When production of squark pairs $\tilde{q}\tilde{q}$ is dominant, only a small number of jets (one per squark from $\tilde{q} \to q\chi_1^0$) is expected. When production involves gluinos, extra jets are expected from $\tilde{g} \to qq\chi_1^0$. In these regions, requiring at least three jets yields better sensitivity. For each of the four signal regions (two dijet and two three-jet selections) E_T^{miss} is required to be > 100 GeV.
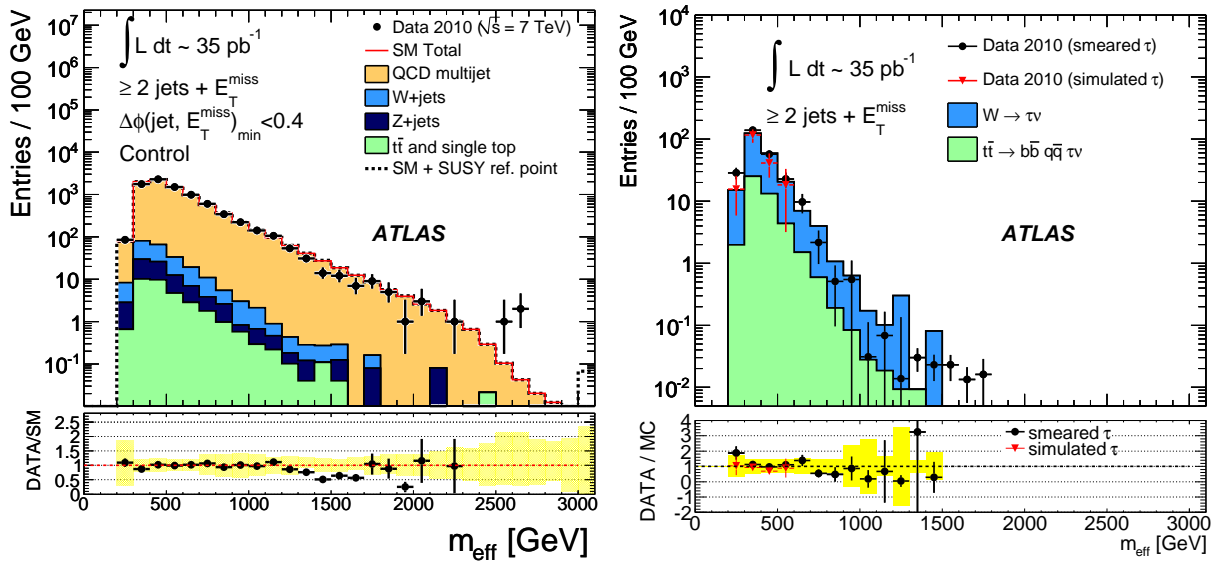
Figure 3: Left plot: Distribution of m_{eff} after the 2-jet and missing transverse momentum selection in the control region defined by the reverse cut on $\Delta\phi$. Right plot: Distribution of m_{eff} for the tau-related background after the full 2-jet selection, except the cut on M_{eff}. Two data-driven background estimates are shown, both derived from selected $W \to \mu\nu$ events. The muon is removed from the event and replaced by a Monte Carlo tau lepton decay, which is either smeared using resolution functions to emulate the detector response (smeared tau) or processed using the full detector simulation (simulated tau).

The signal region aiming for high mass dijet events has a selection criteria on $m_{\text{T2}} > 300$ GeV. The quantity m_{T2} is a generalisation of the transverse mass for two particles decaying to a jet and missing transverse momentum [4]. The other three signal regions are defined with cuts on the effective mass, which is here a sum over the leading two or three jets (depending on the channel) and the missing transverse momentum.

The dominant SM background sources are W+jets, Z+jets, top pair, QCD multijet and single top production. The determination of a solid prediction for these backgrounds in the signal regions is the main challenge in these searches. ATLAS has carried out about $2-4$ control measurements per signal region and background. One method to derive the QCD prediction was a normalisation of the QCD MC samples by a scaling designed to achieve a match to data in control regions obtained by reversing the $\Delta\phi$ requirements. The m_{eff} distribution in the control region is shown in Figure 3. This result was found to be consistent with an other data-driven estimate in which high $E_{\text{T}}^{\text{miss}}$ events were generated from data by smearing low $E_{\text{T}}^{\text{miss}}$ events on a jet-by-jet basis with measured jet energy resolution functions. This latter technique has no MC dependencies; it provides a completely independent determination of the QCD multijet background using only quantities measured from the data. Additional control regions having reversed $E_{\text{T}}^{\text{miss}}/m_{\text{eff}}$ requirements were used as further checks on the normalisation.

The Z+jets background originates from the irreducible component in which $Z \to \nu\bar{\nu}$ generates large $E_{\text{T}}^{\text{miss}}$. This background is measured in control regions were the Z decays to muons or electrons and is also modelled with a W+jets control sample. The W+jets background is determined via the same window in the $(M_T, E_{\text{T}}^{\text{miss}})$ plane as in the 1-lepton channel, but applying the jet cuts of this analysis. Hadronic τ decays in $t\bar{t} \to b\bar{b}\tau\nu qq$ can generate large $E_{\text{T}}^{\text{miss}}$ and pass the jet and lepton requirements at a non-negligible rate. The MC estimate for these events was checked to be consistent with a data-driven cross-check based on replacement of reconstructed muons in the corresponding single lepton channels with simulated hadronic τ decays. The resulting m_{eff} distribution is shown in Figure 3. Agreement was also found after reweighting the $t\bar{t}$ MC according to experimentally measured b-tag weights.
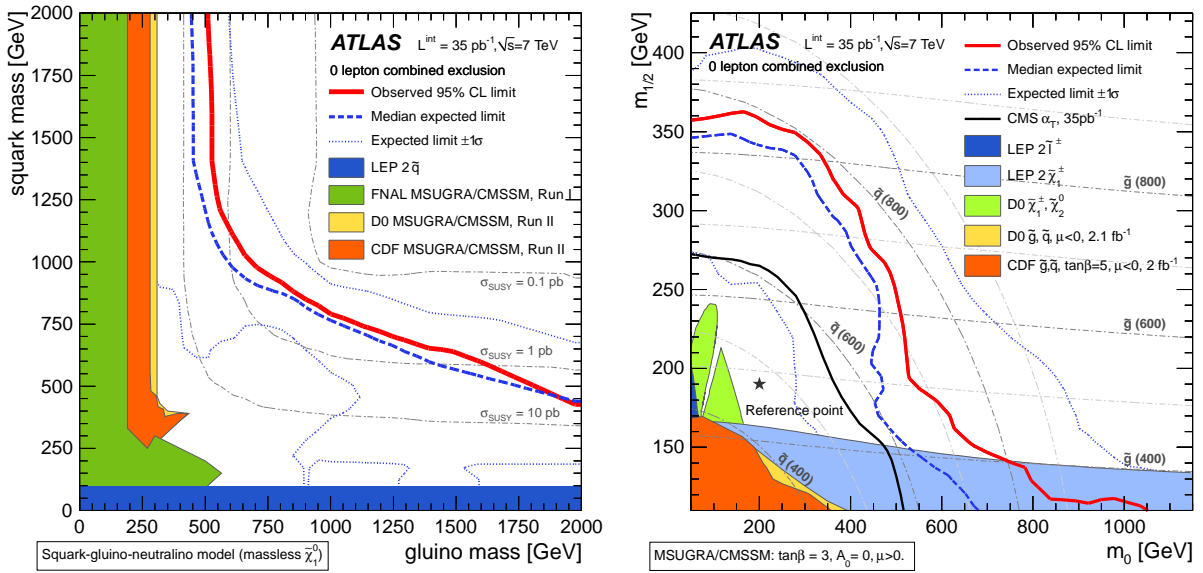
Figure 4: Left plot: 95% C.L. exclusion limits in the (gluino, squark) mass plane together with existing limits for a simplified MSSM model with a massless neutralino. Comparison with existing limits is illustrative only as some are derived in the context of MSUGRA/CMSSM or may not assume a massless neutralino. Right plot: 95% C.L. exclusion limits in the $\tan(\beta) = 3$, $A_0 = 0$ and $mu > 0$ slice of MSUGRA/CMSSM, together with existing limits with the different model assumptions given in the legend.

The number of observed data events and the number of SM events expected to enter each of the signal regions were found to be consistent in all four signal regions. The signal regions exclude again non-SM effective cross sections within acceptance. The results are interpreted in both a simplified model containing only squarks of the first two generations, a gluino octet and a massless neutralino, as well as in MSUGRA/CMSSM models with $\tan\beta = 3$, $A_0 = 0$ and $\mu > 0$. In the simplified model, gluino masses below 500 GeV are excluded at the 95% confidence level with the limit increasing to 870 GeV for equal mass squarks and gluinos. In the MSUGRA/CMSSM models equal mass squarks and gluinos below 775 GeV are excluded. Both exclusion plots are shown in Figure 4.

4 Searches with b-jets and missing transverse momentum

Events with jets, one or no lepton and missing transverse momentum are also studied with a b-tag requirement in order to enhance the sensitivity to the third generation, i.e. stops and sbottom squarks [5].

The 0-lepton b-jet selection uses slightly modified selection criteria compared to what was described above and is optimised for signals like sbottom production (either direct production or via gluino decay to sbottom and bottom) and the subsequent decay $\tilde{b} \rightarrow b\chi_1^0$. The 1-lepton b-jet selection aims for signals of stop production where the stop decays to a sbottom and chargino and finally the chargino could decay leptonically to a neutralino, a lepton and a neutrino. The signature would therefore be b-jets, leptons and missing transverse momentum. In both channels at least one jet is required to be b-tagged. The dominant background source is then top pair production due to this extra b-jet requirement. Again data-driven techniques have been employed to determine the QCD, W+jets and top backgrounds. No significant excess is observed with respect to the prediction for Standard Model processes. For R-parity conserving models in which sbottoms (stops) are the only squarks to appear in the gluino decay cascade, gluino masses below 590 GeV (520 GeV) are excluded at the 95% C.L. The results are also interpreted in an MSUGRA/CMSSM supersymmetry breaking scenario with $\tan(\beta) = 40$ and in an $SO(10)$
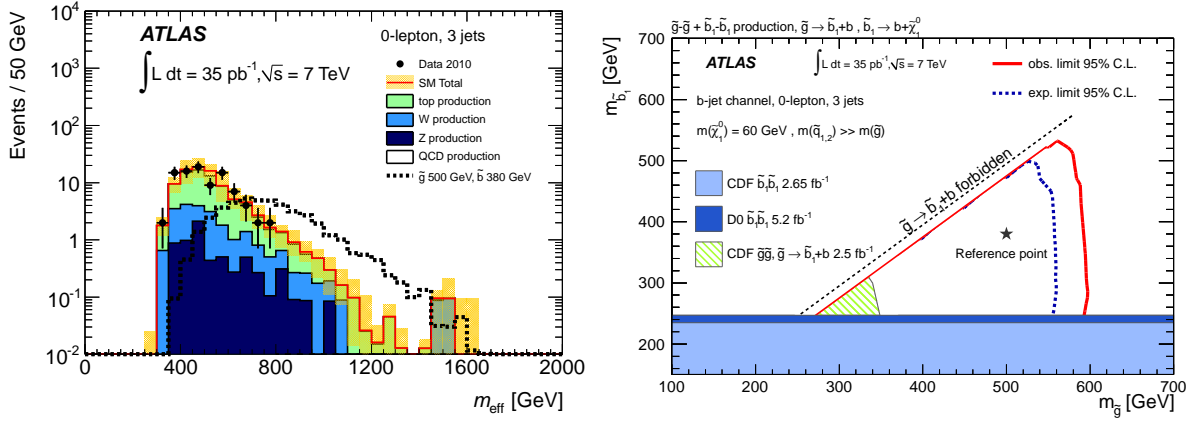
Figure 5: Left plot: Distributions of the effective mass for data and for the expectations from Standard Model processes after the baseline selections in the zero-lepton b-jet channel . Right plot: Observed and expected 95% C.L. exclusion limits, as obtained with the zero-lepton b-jet channel, in the $(m_{\tilde{g}}, m_{\tilde{b}1})$ plane. The neutralino mass is assumed to be 60 GeV. The result is compared to previous results from CDF and D0.

model framework. The m_{eff} distribution for the zero-lepton selection and the resulting limit are shown in Figure 5.

5   Searches with Dilepton events

A very clean potential signal for SUSY particles could come from dilepton events. In addition the shapes and endpoints of the dilepton mass distributions are a potentially perfect source to provide mass information for SUSY particles.

ATLAS has searched for the production of supersymmetric particles decaying into final states with missing transverse momentum and exactly two isolated leptons. The search strategies included events with lepton pairs with identical sign and events with opposite sign electric charges [6]. The signal region for the same sign analysis is defined by $E_{\text{T}}^{\text{miss}} > 100$ GeV, the signal region for the opposite sign analysis requires $E_{\text{T}}^{\text{miss}} > 150$ GeV. The main background of the same sign analysis arises from SM processes generating events containing at least one fake or non-isolated lepton. For the opposite sign analysis the main background arises from SM top pair production. The fake background is estimated by solving linear equations to get the fake probability for a "tight" lepton selections via a "loose" lepton selection. Dedicated control selections are developed to estimate the background from top events. Depending on the flavour of the two leptons $(ee, \mu\mu, \mu e)$ and the electric charge in total 6 signal regions are used for the search. Again no significant excesses are observed. Based on specific benchmark models, limits are placed on the squark mass between 450 and 690 GeV for squarks approximately degenerate in mass with gluinos, depending on the SUSY mass hierarchy considered (see Figure 6). The important (free) parameters of the MSSM model are the three gaugino masses and the squark and slepton masses [6]. The slepton is light in order to enhance the lepton decay.

Dilepton events are also studied with the so called "flavour subtraction" method [7]. Flavour uncorrelated backgrounds are subtracted using a sample of opposite flavour lepton pair events. The dominant background from top pair production can be subtracted via this method. In SUSY events the production of the two leptons can be correlated, if lepton flavor is conserved in the decays of e.g. a heavy neutralino to a slepton and a lepton and subsequently to $ll\chi_1^0$. The search for high missing transverse momentum events containing opposite charge identical flavour lepton pairs yields no significant excess. Here limits are set on the model-independent quantity S , which measures the mean excess from new physics taking into account flavour-dependent
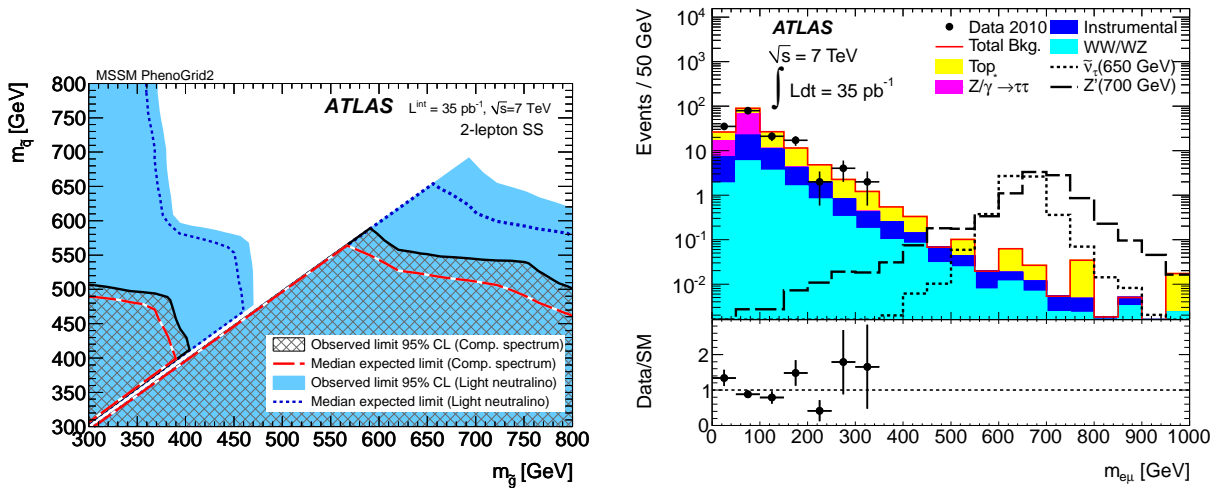
Figure 6: Left plot: Expected and observed 95% C.L. exclusion limits in the $(m_{\tilde{g}}, m_{\tilde{q}})$ plane for a MSSM models for the same sign dilepton analysis. Right plot: Observed and predicted electron-muon invariant mass distributions. The signal simulations are shown for tau-sneutrino with a mass of 650 GeV and a Z' with a mass of 700 GeV.

acceptances and effiencies.

A third generic search is performed for heavy particles decaying into an electron-muon final state [8]. Again the fake backgrounds are carefully determined via data-driven techniques. No excess above the Standard Model background expectation is observed (see Figure 6). Exclusions at 95% confidence level are placed on two representative models. In an R-parity violating supersymmetric model, tau sneutrinos with a mass below 0.75 TeV are excluded, assuming single coupling dominance and the R-parity violating couplings to be $\lambda'_{311} = 0.11$, $\lambda_{312} = 0.07$ (in order to compare with previous Tevatron studies). The ATLAS results extend to higher mass then previously studied at the Tevatron.

6   Searches for new slow-moving massive particles

ATLAS has also pursued a search for slow-moving charged particles (SMPs) [9]. Such particles are expected in some new physics models where the new (SUSY) particles are not allowed to decay, e.g. because the decay goes via highly virtual particles or because the couplings are very small. If these long lived particles are squarks or gluinos they will hadronize and form so called R-hadrons. The signal of such heavy particles will be a slowly moving heavy hadron.

The ATLAS detector contains a number of subsystems which provide information which can be used to distinguish SMPs from particles moving at velocities close to the speed of light. Two complementary subsystems used in this work are the pixel detector, which measures ionisation energy loss (dE/dx), and the tile calorimeter, which measures the time-of-fight from the interaction point for particles which traverse it.

The events are triggered by a E_T^{miss} and track requirement. For each event, the mass is estimated by dividing its momentum by $\beta\gamma$, determined either from pixel detector ionisation or from the tile calorimeter. Rather than relying on simulations to predict the tails of the Pixel and Tile beta distributions, a data-driven method is used to estimate the background. Estimates for the background distributions are obtained by combining random momentum values (after the kinematic cuts) with random measurements of the Pixel and Tile β. This works since no correlation was observed in these three measurements.

Using data combined from these independent measurements, there are no events containing a candidate with mass greater than 100 GeV. This result is interpreted in a framework of
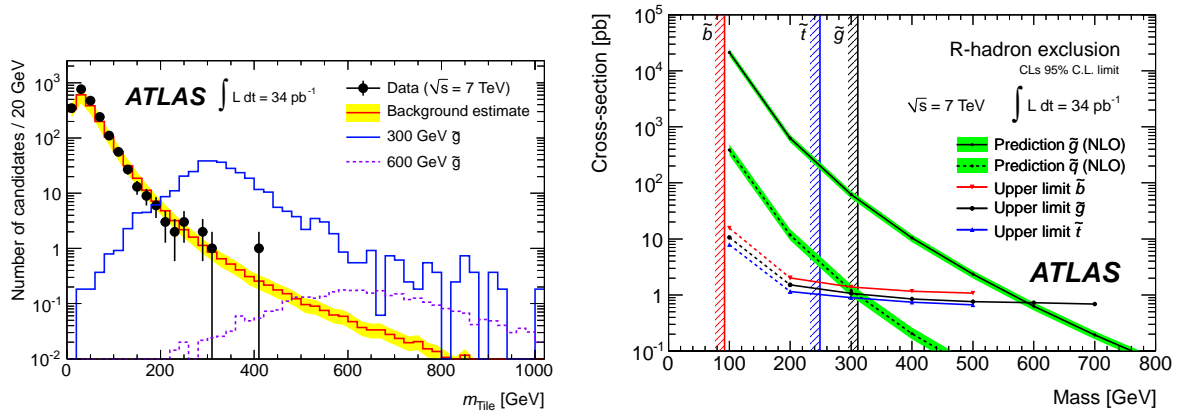
Figure 7: Left plot: The reconstructed mass of the R-hadron candidate and the background estimates for the tile calorimeter. Signal samples are superimposed on the background estimate. Right plot: Cross-section limits at 95% CL as a function of sparticle mass. The mass limits quoted in the text are inferred by comparing the cross-section limits with the model predictions. Previous mass limits are indicated by shaded vertical lines for sbottom (ALEPH), stop (CDF) and gluino (CMS).

supersymmetry models with R-hadrons and 95% CL limits are set on the production cross-sections of squarks and gluinos. The influence of R-hadron interactions in matter was studied using a number of different models, and lower mass limits for stable sbottoms and stops are found to be 294 and 309 GeV respectively (see Figure 7). The lower mass limit for a stable gluino lies in the range from 562 to 586 GeV depending on the model assumed. Each of these constraints is the most stringent to date.

7 Summary and Conclusion

The ATLAS experiment has started to search for signals of Supersymmetry. Due to the large cross sections for squarks and gluinos the sensitivity of the 2010 LHC data exceeds by far that of all previous collider experiments. The search is performed in a variety of different final states. ATLAS has presented the most stringent limits to date in many scenarios and no signal has been observed yet. The next years will likely allow a conclusive answer about the fate of low mass Supersymmetry.

Acknowledgments

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